Optimum boundary element method volume conductor models

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1 Introduction

The Boundary Element Method (BEM) approximates the different compartments of a volume conductor model by closed triangle meshes with a limited number of nodes. The shielding effect of the weakly conducting skull layer of the human head leads to decreasing potential gradients from the inside to the outside of the head. Thus, there may be an optimum distribution of nodes to the different boundaries, resulting in improved accuracy as compared to standard uniform distributions for a given, limited total number of nodes.

We tested the performance of different spherically and realistically shaped models with simulated dipole data against reference solutions from analytical models and highly refined reference models, respectively.

2 Methods

2.1 Spherical models

In order to have a reliable, analytically solvable reference model, first a spherical approximation consisting of three concentric shells was chosen for the simulations. The three boundary surfaces were modeled by approximately 3000, 2000, 1000, and 500 nodes each. All possible combinations lead to 64 different models with total numbers of nodes between 9000 and 1500. Furthermore, the influence of the electrode positions relative to the nodes of the outer compartment was studied by including them as nodes or not. 81 electrodes were placed on an extended 10/20-system grid. The triangles were globally virtually refined and a regionally constant potential approximation was chosen over the sub-triangles [1]. For improved accuracy, the Isolated Problem Approach (IPA) [2] was used during the BEM model set-up.

Potential distributions of 4000 test-dipoles at random positions inside the innermost compartment and with random orientations were calculated analytically as reference solution. All dipole data were then fitted by single dipoles using the 128 different BEM models and mean and maximum localization errors were evaluated. The true dipole positions were used as start positions for the fit procedure.

2.2 Realistically shaped models

Similar to the spherical cases, realistically shaped BEM compartments were constructed from averaged magnetic resonance (MR) data (Montreal Neurologic Institute) by an automated procedure [3].

Since no analytical solution exists in this case, the highly refined 9000 nodes model was used as reference for the forward calculations (again for 4000 randomly distributed test-dipoles with random orientations inside the innermost compartment). Several BEM models with less refined compartment meshes were then used to fit the dipole data and to determine mean and maximum localization errors.

Since from the results of the spherical cases it was obvious that electrodes on nodes of the outermost compartment lead to smaller localization errors (see Results), the different realistically shaped skin meshes were set-up with nodes at the electrode positions only, leading to 64 different models.

The different model compartments with electrode and test-dipole positions are shown in Figs. 1 and 2 for the spherical cases. Figs. 2 and 3 display the models of the realistically shaped cases. Mean triangle side lengths and number of nodes of all models used are listed in Table 1.

All computations were performed using the Curry V4.5 software package (Neuroscan).

Table 1: Mean triangle side lengths and number of nodes for spherical and realistically shaped set-ups.

	spherical shells		realistic. shaped	
compartment	Δ-size [mm]	nodes	Δ-size [mm]	nodes
Skin3	7.2	2933	7.6	2882
Skin2	8.7	1988	9.1	2003
Skin1	12.6	961	12.4	1014
Skin05	17.8	479	17.7	532
Skull3	6.6	2973	6.5	2836
Skull2	8.1	1973	7.7	2012
Skull1	11.4	1001	10.8	1014
Skull05	16.1	520	15.4	500
Brain3	6.1	3012	5.9	3040
Brain2	7.4	2007	7.3	1979
Brain1	10.5	1002	10.0	1038
Brain05	14.8	503	14.3	500

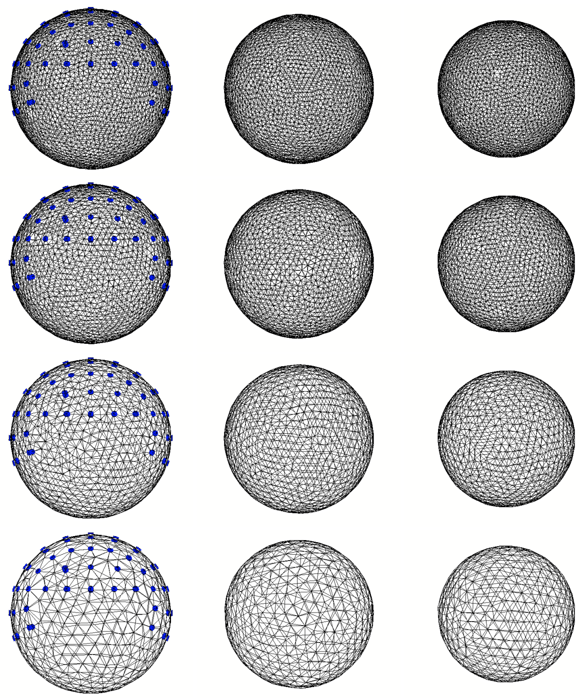

Figure 1**:** *Spherical shell models for BEM simulations. Left to right: outer, middle, and inner shells, top to bottom: 3000 nodes, 2000 nodes, 1000 nodes, and 500 nodes.* 4^3*=64 combinations are possible.*

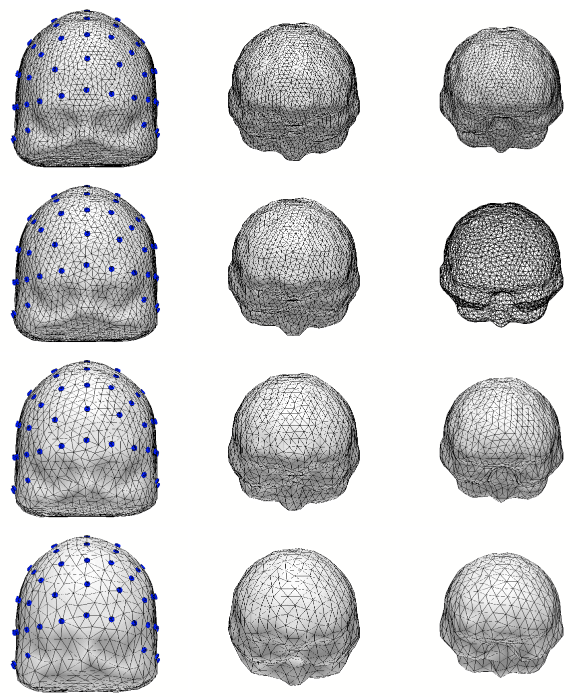

Figure 3**:** *Realistically shaped compartments for BEM simulations. Left to right: skin, skull, and brain compartments, top to bottom: 3000 nodes, 2000 nodes, 1000 nodes, and 500 nodes. Frontal views.*

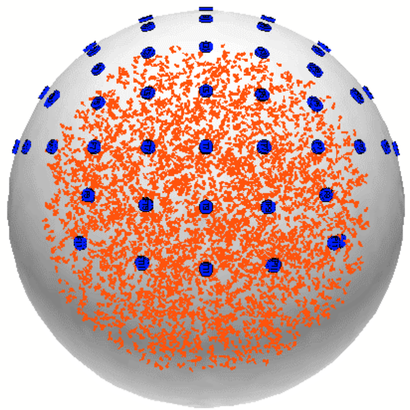

Figure 2**:** *4000 randomly distributed test-dipoles inside the innermost spherical shell, 81 electrodes.*

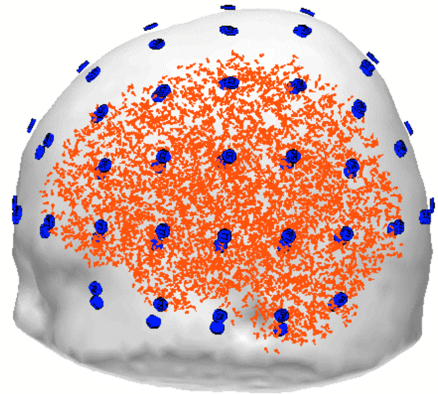

Figure 4**:** *4272 randomly distributed test-dipoles inside the brain compartment, 81 electrodes. Left side view.*

3 Results

3.1 Spherical models

Mean and maximum localization errors for all 128 different BEM models are shown in Fig. 5. The results are shown for the 2000 dipole positions in the more interesting upper hemisphere only. Obviously the errors decrease with increasing number of nodes. Models with nodes at electrode positions exhibit smaller errors. Another striking result is, that the localization accuracy does not only depend on the total number of nodes, but also on the distribution of nodes to the different compartments. Reordering the results of the cases with nodes at electrode positions reveals this dependency more clearly as displayed in Fig. 6. The worst results are obtained when at least one compartment has 500 nodes only. The maximum error mainly depends on the number of nodes of the innermost compartment. With at least 1000 nodes per compartment relatively good accuracy can be achieved, but for optimum performance more nodes are needed for the innermost compartment.

The evaluations for dipoles in the lower hemisphere show similar results with larger overall errors.

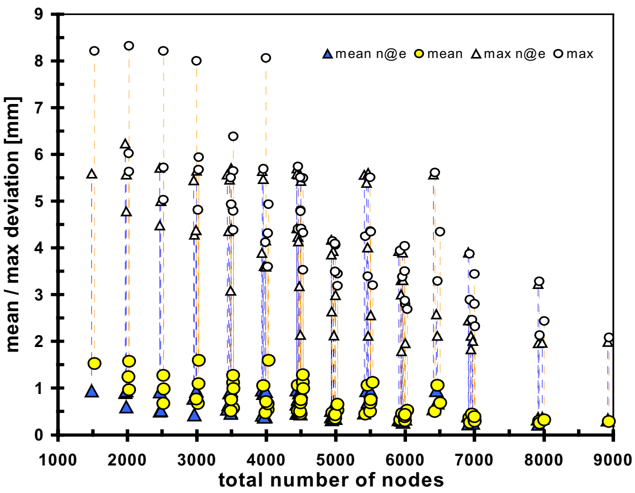

Figure 5: *Mean (large symbols) and maximum (small symbols) localization errors for 128 different spherical BEM-modes as a function of the total number of nodes for 2000 test-dipoles in the upper hemisphere. Triangle symbols represent models with nodes at electrode positions, whereas circles show models with outermost compartment meshes independent of the electrodes.*

3.2 Realistically shaped models

Similar to the spherical cases, the results of the realistically shaped BEM models are evaluated. Fig. 7 shows the mislocalizations of the coarsest BEM model with 1500 nodes in total. For the statistical evaluations (Fig. 8) the test-dipoles in the cerebellum, which are not very relevant and exhibit the largest errors, are omitted, leaving 4066 of the 4272 random positions. Fig. 8 displays the localization errors for the different BEM models in the same order as for the spherical cases in Fig. 6.

The results for the realistically shaped models exhibit a similar behavior as the spherical models studied before. At least 1000 nodes per compartment are needed for a reliable model and the largest errors, that occur for the most superficial test-dipole positions, are dominated by the innermost compartment only.

For comparison, dipole fit results using a three spherical shells model fitted to the 71 electrodes are also shown in Fig. 8. The spatial distribution of the localization errors is depicted in Fig. 9. As expected and known from earlier studies, positions in the non-spherical lower parts of the head model are affected strongest.

4 Discussion

The bilinear interpolation, that is necessary to calculate the potential at the actual electrode position, which is not at a node of the outermost

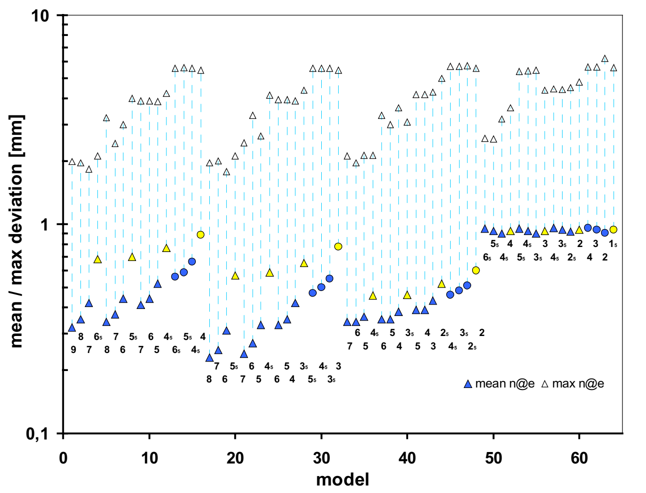

Figure 6: *As Fig. 5 for 64 different spherical BEM-models with nodes at electrode positions. From one model to the next the number of nodes of the outermost compartment is changed (3000, 2000, 1000, 500 (light symbols)). Then the innermost compartments (circles mark 500 nodes) are varied in the same way and finally the middle compartment is changed: model 1 to 16: 3000 nodes, model 17 to 32: 2000 nodes, model 33 to 48: 1000 nodes, model 49 to 64: 500 nodes. Small numbers below symbols indicate the total number of (kilo-)nodes.*

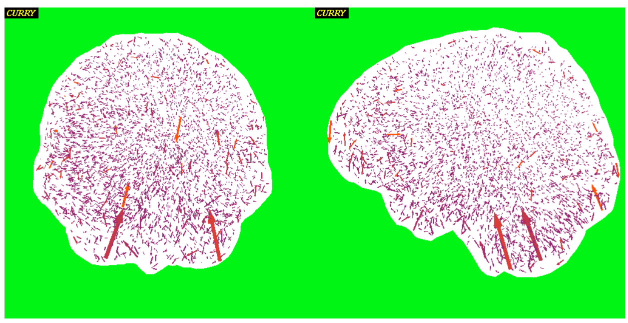

Figure 7: *Dipole mislocalizations due to a coarse BEM-model (500 nodes per compartment). Forward calculations using a highly refined reference BEM-model (3000 nodes per compartment). Arrows connect true and fitted test-dipole positions. Front and left side views.*

compartment, introduces errors, especially for coarse meshes. Thus, it is advantageous to include the (projected) electrode positions into the meshing algorithm for this compartment.

500 nodes per compartment result in a too coarse representation of both spherical and realistically shaped models. Even if only one compartment is set-up using such a coarse mesh, large localization errors occur.

The largest mislocalizations can be found for superficial source positions, as could be expected from

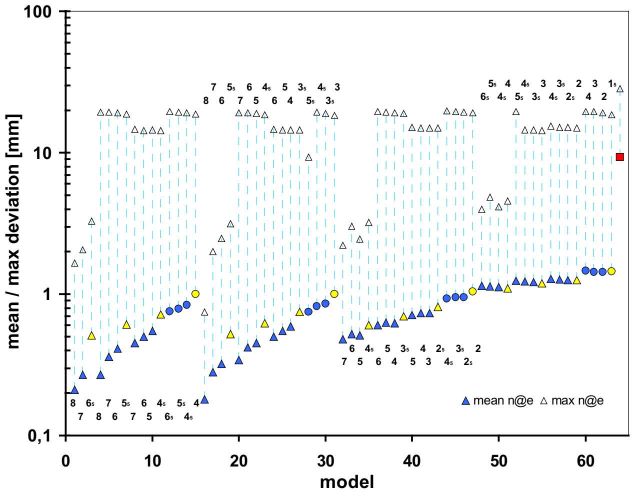

Figure 8**:** *As Fig. 6 for 63 different realistically shaped BEM-models with nodes at electrode positions. From one model to the next the number of nodes of the outermost compartment is changed (3000, 2000, 1000, 500 (light symbols)). Then the innermost compartments (circles mark 500 nodes) are varied in the same way and finally the middle compartment is changed: model 1 to 15: 3000 nodes, model 16 to 31: 2000 nodes, model 32 to 47: 1000 nodes, model 48 to 63: 500 nodes. Small numbers indicate the total number of (kilo-)nodes. For comparison a three spherical shells model was used as well (model 64). The reference model (9000 nodes) is not shown.*

earlier publications. These positions close to the innermost compartment suffer most from too coarse approximations of the actual volume conductor shape. Thus, the maximum errors mainly depend on the refinement of the innermost compartment mesh. The mean errors are less affected by the individual meshes, as long as all compartments consist of 1000 nodes at least.

From Fig. 6 and 8 it can be seen, that e.g. for 6000 nodes overall, 3000, 2000, and 1000 nodes (inner, middle, and outer compartment) result in the best achievable model (no. 19). For 4000 nodes overall, model 39 (2000, 1000, 1000 nodes) performs best.

The effects seen can be explained by the potential gradients that decrease from the innermost to the outermost compartment, due to the low conductivity of the middle layer. The nodes of the triangle meshes, that reflect the actual shape of the compartments, discretize and sample the actual potential distributions and the BEM approximates the potential changes over the triangles by constant, linear, or regionally constant dependencies. In order to better represent the fast potential changes on the innermost boundary, small triangle sizes (node distances) are necessary, especially for this compartment border and for superficial sources.

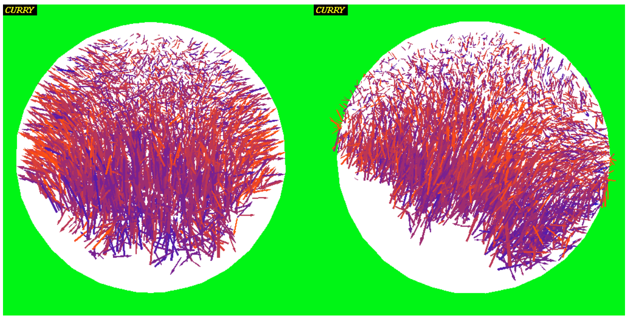

Figure 9**:** *Dipole mislocalizations due to an over-simplifying three spherical shells model. Forward calculations using a highly refined reference BEM-model (3000 nodes per compartment). Arrows connect true and fitted test-dipole positions. Front and left side views (compare Fig. 7 and Fig. 8, model 64).*

In conclusion, we have shown in the most extensive study we are aware of (192 different BEM models with up to 9000 nodes, over 800000 dipoles fitted), that it is favorable to set-up the innermost compartment using about half the total number of nodes (in order to limit the maximum error of superficial sources) and that the middle and outer meshes should contain at least 1000 nodes to reduce the mean localization error.

MEG volume conductor models are less critical than EEG models: The properties of the innermost compartment dominate the field distributions, since in the middle and outer compartments rather small secondary currents are imposed, which contribute as correction terms only [2]. Furthermore, the magnetic fields are sampled by sensors relatively far away from the sources, so no final potential interpolation as in the electric case is necessary.

References

1. M. Fuchs, R. Drenckhahn, H.-A. Wischmann, M. Wagner, “An Improved Boundary Element Method for Realistic Volume-Conductor Modeling”, *IEEE Trans. Biomed. Eng.* **45**, 980-997, 1998.
2. M.S. Hämäläinen, J. Sarvas, “Realistic Conductivity Geometry Model of the Human Head for Interpretation of Neuromagnetic Data”, *IEEE Trans. Biomed. Eng.* **36**, 165-171, 1989.
3. M. Wagner, M. Fuchs, R. Drenckhahn, H.-A. Wischmann, Th. Köhler, A. Theißen, "Automatic Generation of BEM and FEM Meshes", *NeuroImage* **5**, 389, 1997.